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The longleaf pine forest: Long-term monitoring and restoration of a management dependent ecosystem

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ABSTRACT

Conservation and restoration of biodiversity and ecosystems is increasingly important due to negative impacts caused by expanding human populations, changing land use, and climate change. Understanding drivers of system processes supports efficient restoration and successful conservation of biodiversity and ecosystems. We describe a long-term forest monitoring program established as a component of a long-term ecological monitoring approach and used in conjunction with adaptive management to actively restore a longleaf pine (*Pinus palustris*) system. Eight panels of 108 monitoring points were selected within our 11,740 ha study area near Newton, GA, USA using a Random Tessellation Stratified design with hierarchical randomization. Each year two panels were sampled, resulting in a complete survey of all points every four years. To date, data have been collected over four sampling intervals (2002–2017). Collected data included basic forestry measurements and quantification of understory conditions. For an initial analysis of the data, we calculated estimates and error of average volume, change in volume, mortality, diameter distribution, and ingrowth. Additionally, we compared effects of management practices, which varied between plots, on these estimates. The tree volume on the study area is comprised primarily of longleaf pine with ~80% of this volume from trees ≥34 cm DBH. Pine tree volume increased by 13.29 (± 2.03) m^3/ha between Intervals 1 and 4. Pine mortality during each sample interval was relatively stable over the study period, 2.98 (± 0.39) - 4.56% (± 0.58), and primarily attributed to timber harvest. Management activities resulted in increased longleaf pine ingrowth and reduced hardwood volume. Our analyses indicate that through our management actions we have successfully made progress towards achieving our overall restoration goals for the site. Data collected from the long-term monitoring program were also used to provide information for scientific studies regarding water conservation in longleaf pine systems and wildlife-habitat relationships. As monitoring progresses, collected data will be used to assess progress and guide further restoration using adaptive management and dynamic reference models.

1. Introduction

Conservation and restoration of biodiversity and ecosystems is increasingly important due to negative impacts caused by expanding human populations, subsequent changes in land use, and climate change. Understanding what drives system processes is necessary for efficient restoration and successful conservation of biodiversity and ecosystems. Systems may require management for conservation or restoration and understanding how management activities affect system processes will aid in achieving conservation and restoration goals (Fancy & Bennetts, 2012).

Long-term monitoring, dynamic reference models, and adaptive management are all methods used in the conservation and restoration of systems and populations (Fancy & Bennetts, 2012; Hiers et al., 2012; Walters & Holling, 1990). These methods allow for increased understanding of system processes and more efficient management. One of the benefits of long-term monitoring data is the potential to understand drivers of ecological processes and phenomena that occur over long temporal scales, including distinguishing between anthropogenic and natural changes (Lindenmayer & Likens, 2010b; Magurran et al., 2010; Possingham, Fuller, & Joseph, 2012; Smith, Purcell, & Barimo, 2007). Additionally, long-term monitoring can be used as a warning system to detect unusual conditions, potential concerns, or unwanted changes in resources (Bennetts et al., 2007; Lindenmayer & Likens, 2010b). Despite the utility of long-term monitoring programs, many fail due to lack of support, collaboration, adaptability, and scientific productivity

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(Lindenmayer & Likens, 2010b, 2009).

Loss of ~95% of longleaf pine (*Pinus palustris*) forests across the southeastern United States in the species' historical range has increased interest in the restoration and management of this diverse ecosystem. Land conversion to agriculture and plantations of fast growing pines (e.g., loblolly pine [*Pinus taeda*] and slash pine [*Pinus elliotti*]) for timber production along with fire suppression are the primary causes for loss of longleaf pine forests (McIntyre, McCall, & Wear, 2018; Ware, Frost, & Doerr, 1993). The longleaf pine ecosystem has a high diversity of flora and fauna which are affected by changes to the natural disturbance regime. Lack of frequent fire in a longleaf pine system leads to the release of mesic hardwoods (e.g., oaks [*Quercus* sp.] and sweetgum [*Liquidambar styraciflua*]) into the midstory and ultimately changes in the understory, including increased presence of fire intolerant species and a reduction in herbaceous groundcover (Mitchell, Hiers, O'Brien, Jack, & Engstrom, 2006; Waldrop, White, & Jones, 1992). Introducing frequent prescribed fire, removal of hardwoods, and reintroduction of extirpated species are all potential management actions for the restoration of longleaf pine ecosystems (Jack & McIntyre, 2018). Understanding the effects of restoration and management practices, and the time scale of these effects, is important to facilitating recovery of longleaf pine ecosystems (Brockway, Outcalt, Tomczak, & Johnson, 2005; Waldrop et al., 1992). Monitoring effects of longleaf pine restoration activities can be used to determine success of restoration and improve the implementation of management actions (Sutter & Rutledge, 2018).

The Joseph W. Jones Ecological Research Center (Jones Center) began monitoring efforts on its land base, Ichauway, in the early 1990's. Early monitoring efforts included censuses of specific wildlife populations and communities, forest inventory, and climatological and hydrological characteristics. In 2001, a long-term ecological monitoring program that serves to integrate ongoing efforts and incorporate new, more structured monitoring data was initiated (Table 1). The long-term ecological monitoring program is a comprehensive effort to characterize the current ecological condition of Ichauway and to address questions regarding change through time and with active management. Specific objectives include the description and quantification of: 1) ecosystem and land cover diversity and the dynamics of forest and non-forest habitats; 2) the vegetative and structural parameters of wildlife habitat; 3) the effects of management on forest structure, non-forested habitats, and wildlife populations; and 4) progress in meeting restoration goals for some degraded habitats and maintenance of intact habitats on the property. This long-term ecological monitoring effort will provide the necessary information for an adaptive management approach to meet management and restoration objectives.

Our objectives for this manuscript were to provide an initial analysis of forest structure change at Ichauway using long-term monitoring data (16 years) to illustrate how our collection methods can document the impacts of management on meeting our longleaf pine restoration goals. In addition to the overall assessment of forest change, we wanted to better understand how management practices influenced forest structure and dynamics. To do this we compared restoration treatments (i.e., hardwood removal and planting of pine) against routine management practices which included timber harvest and prescribed fire. Additionally, we discuss how monitoring information will enlighten an adaptive management approach for our study area and help guide the development of dynamic reference models (Hiers et al., 2012; Kirkman et al., 2013).

2. Materials and methods

2.1. Study area

Ichauway is the Jones Center's land base (11,740 ha) located in the Dougherty Plain of southwestern Georgia (Fig. 1). Prior to settlement, the vast majority of Ichauway consisted of longleaf pine forest with an herbaceous, wiregrass (*Aristida stricta*) dominated understory. In the late 1800s through early 1900s, the area was extensively logged and some forested areas converted to row crop agriculture (e.g., corn [*Zea mays*], cotton [*Gossypium* sp.], and peanuts [*Arachis hypogaea*]). More recently, Ichauway was the private quail (*Colinus virginianus*) shooting preserve of Mr. Robert W. Woodruff, the long-time leader of the Coca-Cola Company. During this period, the primary management objective for Ichauway was the promotion of quail populations. Management included the annual use of prescribed fire, primarily in the dormant to

Table 1
Long-term monitoring activities conducted by the Jones Center on Ichauway near Newton, GA, USA.

Type	Activity	Year Initiated	Frequency	Current Methodology
Ecosystem	Long-term forest	2001	¼ of plots/year	This paper; (similar to USDA Forest Service, 1999)
	Wetland water levels	1998	2 weeks when flooded	Subset of wetlands have been instrumented for continuous measurements
	Wetland water quality	1998	3 times/year	Early, mid-, and late hydroperiod – subset of wetlands
	Surface water quality	1993	Monthly	Lower Flint River Basin and tributaries
	Stream flow	1995	Continuous	Ichawaynochaway Creek gauge maintained by USGS
	Weather stations	Variable	Continuous	Maintained by GAEMN and NOAA
Community	Breeding birds	1994	Annually	Fixed-radius point count; (Hamel et al., 1996; Ralph, Droege, & Sauer, 1995)
	Mammalian tracks	1997	Annually	(Daniel & Frels, 1971)
	Classified land cover	1993	Variable	Aerial photography interpretation, ground truth, classification
	Aquatic invertebrates	1998	Variable	Standardized dip-net surveys at isolated wetlands; (Battle & Golladay, 2001)
	Rare amphibians	2002	Annually/variable	Standardized dip-net surveys at isolated wetlands; (Shaffer et al., 1994)
Species	Red-cockaded woodpeckers (*Leuconotopicus borealis*)	1993	Annually	(US Fish & Wildlife Service, 2003)
	Gopher tortoises (*Gopherus polyphemus*)	2006	Every 5 years	Line-transect distance sampling; (Buckland et al., 2001; L. L. Smith, Linehan, Stober, Elliott, & Jensen, 2009)
	American alligators (*Alligator mississippiensis*)	2007, 2009	Variable	Double observer line-transect distance sampling; (Buckland et al., 2001)
	Northern bobwhite (*Colinus virginianus*) coveys	2007	Annually	Fixed-radius point count; (Wellendorf, Palmer, & Bromley, 2004)
	Northern bobwhite harvest	1993	Annually	Hunter reported
	White-tailed deer (*Odocoileus virginianus*) population	1993	Annually	Line-transect distance sampling; (Buckland et al., 2001)
	White-tailed deer harvest	1993	Annually	Hunter reported; (Rutledge, Cherry, Cohen, Howze, & Johnson, 2016)
Management	Prescribed fire	1993	Annually	GPS; evaluation
	Timber harvest	1997	Variable	GPS
	Hardwood removal	1993	Variable	GPS
	Pine planting	1938	Variable	GPS, aerial photography, maps

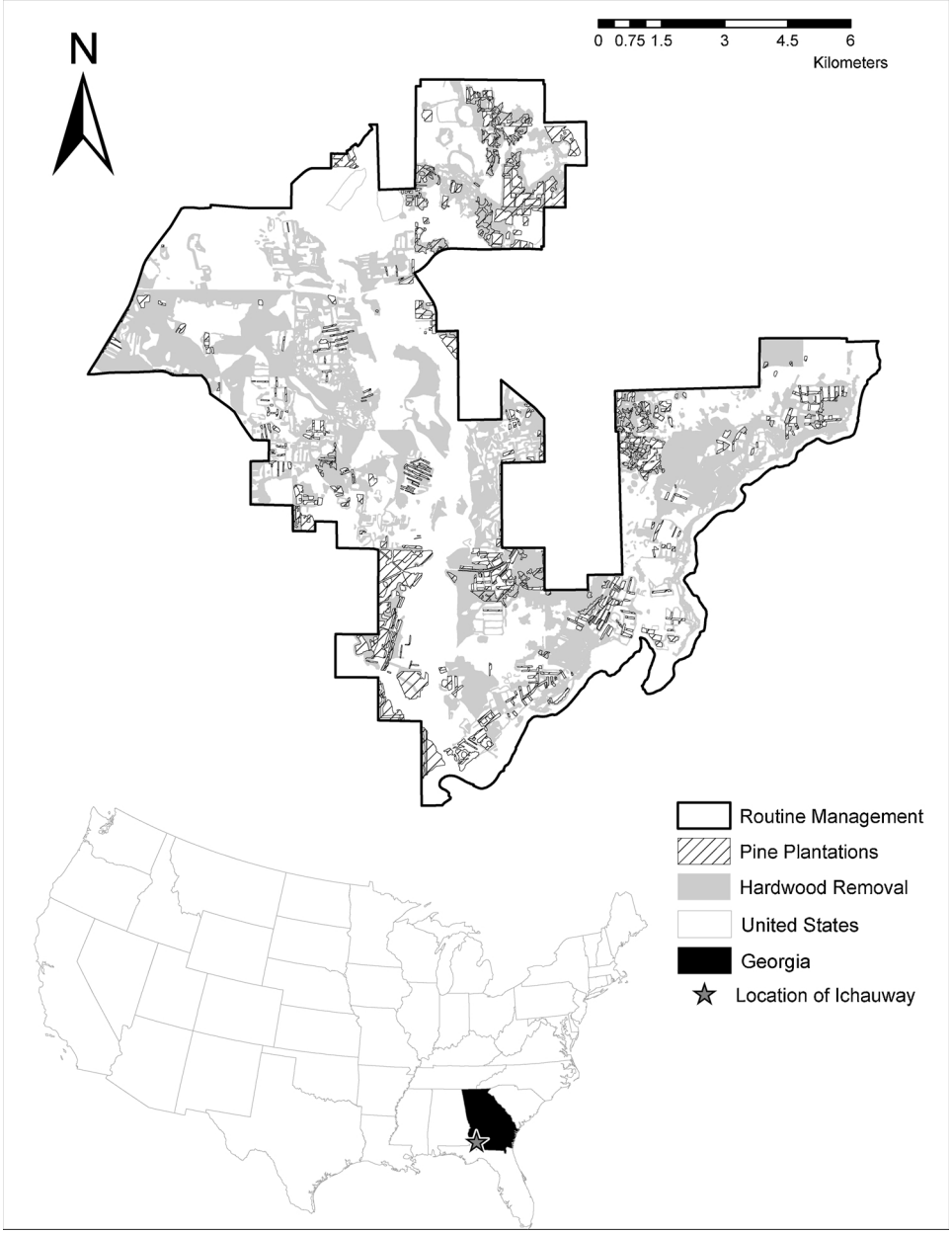

Fig. 1. Study area, Ichauway, boundary and location within Georgia, USA with hardwood removal and pine plantation activities.

early growing season (March and April). In the center of the historical range of the longleaf pine ecosystem, Ichauway represents a remaining fragment of this once extensive, fire-dominated system and is generally representative of a mesic longleaf pine site. A large portion (approximately 7285 ha) of the property has naturally regenerated second-growth, longleaf pine-dominated forest. Much of this forest contains highly diverse native ground cover, with more than 1100 vascular plant species (Drew, Kirkman, & Gholson, 1998; Kirkman, Mitchell, Helton, & Drew, 2001). The remainder of the habitat types on the property include both natural and planted slash pine and loblolly pine, mixed pine-hardwood, and riparian hardwood forests; isolated depressional wetlands; small agricultural fields; and shrub-scrub uplands (Goebel et al., 2001). The Flint River forms the 21-km eastern boundary of Ichauway and about 24 km of Ichawaynochaway Creek flows through the center of the property. These habitats support 61 fish, 31 amphibian, 53 reptilian, 191 avian, and 41 mammalian species (L. L. Smith et al., 2006). Average annual precipitation for the site from 2001 to 2017 was 1260 mm, with an average temperature of 18.7 °C, a mean annual low temperature of 12.8 °C, and mean annual high temperature of 26.1 °C (www.weather.uga.edu).

Broad management and restoration objectives for a large portion of the property include maintaining and increasing longleaf-pine dominated canopy, with an open mid-story and a highly diverse, native, herbaceous understory. Routine prescribed fire is the primary management tool implemented on Ichauway. Fires are conducted biennially in either the dormant (October – March) or growing season (April – September), with a greater emphasis on frequency than seasonality. Management of forest resources uses a modification of the Stoddard-Neel approach (Jack & McIntyre, 2018; Moser, Jackson, Podrazsky, & Larsen, 2002) to maintain a multi-aged forest in perpetuity and restore the longleaf pine ecosystem. Pine timber harvest under this approach utilizes a conservative individual-tree selection method. Since the establishment of the Jones Center, pine timber harvest has been limited and primarily conducted as a function of restoration, demonstration, or research (1280 ha). Portions of the property requiring restoration of the longleaf pine ecosystem and associated plant and animal communities

Table 2
Descriptions of long-term ecological monitoring (LTM) communities on Ichauway near Newton, GA, USA including representative tree species and the original communities from the ecological classification system (ECS) that were combined to create the LTM community.

LTM Community	Description	Representative Trees	Combined ECS Communities
Dry Terrace	Dry deep sands associated with fluvial features	*Pinus palustris*; *Pinus taeda*; *Quercus stellata*; *Quercus laevis*; *Quercus incana*; *Quercus margaretta*	Well drained fluvial terrace Excessively drained fluvial terrace Fluvial sand ridge Terrace escarpment
Flatwoods	Flat, hydric soils and hammocks	*P. palustris*; *Pinus elliottii*; *Q. incana*; *Diospyros virginiana*	Somewhat poorly drained upland terrace Moderately drained upland terrace Depression margin
Floodplain	Floodplain adjacent to creek or river	*Quercus nigra*; *Quercus virginiana*; *Carya glabra*; *Juniperus virginiana*; *Liquidambar styraciflua*; *Celtis laevigata*	Mesic hardwood hammock Floodplains along the Flint River Floodplains along Ichawaynochaway Creek
Fluvial Terrace	Fluvial terrace associated with creek or river	*P. palustris; P. taeda; Pinus echinata; Q. nigra; Q. stellata*	Somewhat poorly drained fluvial terrace Moderately drained fluvial terrace
Intolerant Depression	Wetlands in upland habitat rarely maintained with fire	*Q. virginiana*; *Q. nigra*; *Quercus laurifolia*; *Nyssa sylvatica*; *Taxodium ascendens*	Clayey depression Organic, hydric depression
Sand Ridge	Deep sand ridges in upland habitat	*P. palustris*; *Q. incana*; *Q. laevis*; *Q. margaretta*	Somewhat excessively drained upland terrace Upland sand ridge
Tolerant Depression	Wetlands in upland habitat maintained with fire	*P. palustris*; *P. elliottii*; *Q. geminata*; *Q. virginiana*; *T. ascendens*	Sandy depression Clayey, hydric depression Sandy, hydric depression Hydric flats
Upland	Upland habitat	*P. palustris*; *Q. incana*	Well drained upland terrace

may receive additional treatments. Removal of off-site hardwood species (predominantly species of oak typically occurring in more mesic or riparian areas) from upland communities using mechanical and chemical control measures has been carried out on 3869 ha to date. In addition, longleaf pine seedlings (or other pine species where appropriate) have been planted in areas where adequate longleaf pine canopy is not present to provide seed for natural regeneration. These areas, totaling 1179 ha to date, are primarily in former agricultural fields or where hardwood trees were removed.

The Jones Center developed an ecological classification system (ECS) for Ichauway in 1997 with 21 ecotypes based upon geomorphology, soil, and current vegetation characteristics (Goebel, Palik, Kirkman, & West, 1997). For the purposes of the long-term ecological monitoring program, ECS ecotypes with similar physiography and fire tolerance characteristics were combined into 8 broad ecological communities (Table 2). These communities are: upland (61.7%), sand ridge (10.0%), dry terrace (9.3%), flatwoods (5.4%), fire intolerant depression (4.8%), fluvial terrace (3.4%), floodplain (3.3%), and fire tolerant depression (1.9%).

2.2. Survey design and forest data collection

We selected monitoring points across Ichauway using a Random Tessellation Stratified design with hierarchical randomization (Stevens, 1997). Eight panels of 108 points were created for a total of 864 points. Each panel was a spatially balanced sample, but a proportionally higher number of points were selected in communities with the least cumulative hectares to ensure adequate representation of all communities in each panel. We modeled long-term forest monitoring (LFM) plot design after the United States Forest Service (USFS), Forest Inventory and Analysis Program (FIA; USDA Forest Service, 1999). At each point, we recorded measurements at four distinct sampling levels. One circular plot with a 56-m radius (1 ha) and two interior 18-m radius (0.1 ha) sub-plots were established at each point. The center point of the interior sub-plots were located 18-m north and south of the plot center point. Each sub-plot contained a 9-m radius (0.025 ha) sub-plot core and 2.1-m radius (0.0013 ha) micro-plot (Fig. 2). Plot center and sub-plot centers were located at each randomly chosen point using GPS, and metal stakes and survey caps with plot identification number were installed at each sub-plot center. A witness tree was marked for each sub-plot when possible. Each plot, sub-plot, sub-plot core, and micro-plot was sampled once every four years during the summer (May – August). Sample intervals are four year blocks during which all plots available were sampled.

For the initial LFM survey (2002–2005), only four of the available panels (432 plots) were sampled and we collected data within both sub-plots at each plot. After a programmatic review in 2005, adjustment to the total number of plots increased sampling intensity and reduced coverage error by including the four previously un-sampled panels (432 plots). Starting in 2006 all 864 plots were available to be sampled every four years, but logistical constraints resulted in fewer sampled plots during each interval (minimum sampled 854). During these surveys data were collected at one sub-plot within each plot.

The scope of LFM data collected varied by sampling level within the plot and changed over time. For the purposes of this manuscript, and in general, most of the data were collected at the sub-plot level and below. Within the sub-plot, we identified all trees $\geq$ 10 cm diameter at breast height (DBH; stem diameter at 1.37 m) to species, measured DBH with calipers, mapped each tree (azimuth and distance from sub-plot center), and assigned a tree history code (i.e., live tree, standing dead tree, fallen dead tree, or harvested tree). We also measured length and diameter at each end of coarse woody debris in areas that burned regularly, and canopy cover using a densiometer (Lemmon, 1956). We noted management activities (e.g., timber harvest, hardwood removal, mowing, and herbicide use), the presence of invasive plant species (e.g., Japanese climbing fern [*Lygodium japonicum*], Chinaberry tree [*Melia azedarach*], and Mimosa tree [*Albizia julibrissin*]), and mapped land cover (25 habitat classes within forest, agriculture, wetland, and urban/road land cover types) within each sub-plot. In the sub-plot core, we measured total tree height (from tree base to tip of highest branch) with a laser hypsometer, assigned each tree a crown class (i.e., open grown, dominant, co-dominant, or suppressed), and noted any tree defects (e.g., forked, crooked, broken top, and fire scar) for each tree. We used the micro-plot to sample the understory within the sub-plot. Micro-plot measurements included categorization of plant species groups (i.e., grasses, forbs, woody, vines, ferns) and a count of woody stems (seedlings, < 2.54 cm DBH and saplings, > 2.54 cm and < 10 cm DBH).

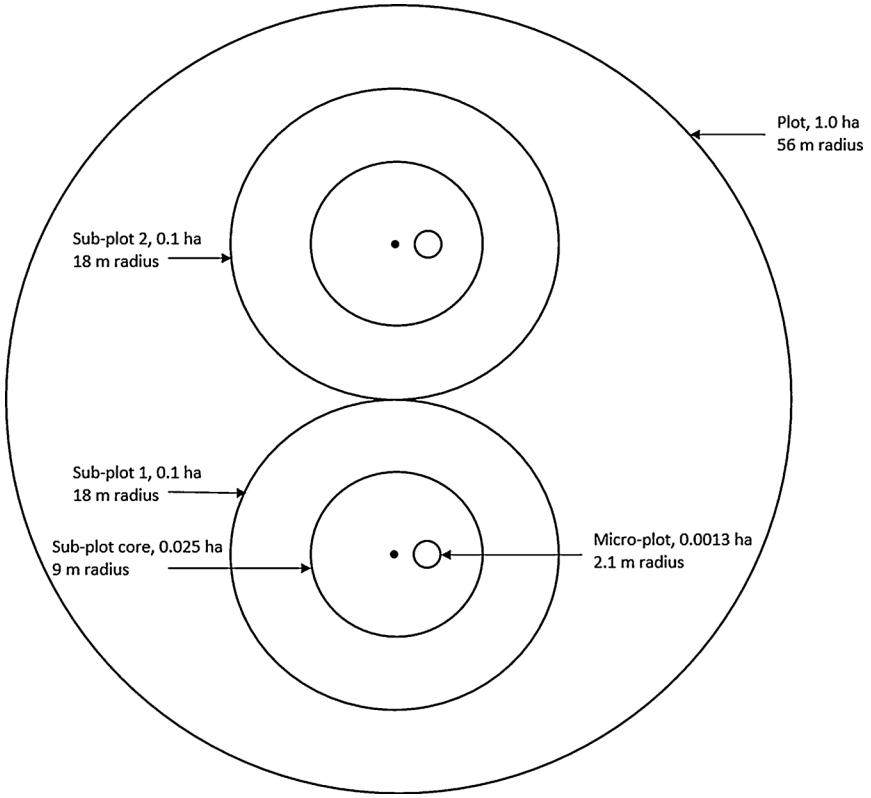

Fig. 2. Plot, sub-plot, sub-plot core, and micro-plot layout for long-term forest monitoring at Ichauway near Newton, GA, USA. Center points of sub-plots are located 18-m north and south of plot center point.

2.3. Initial LFM data analyses

Our first analysis of the LFM monitoring data focused on estimating forest composition and structure and changes in these characteristics between sampling periods, due both to natural stand dynamics and management activities. In particular, we examined management impacts of hardwood removal and pine planting. Because forests change and respond to management relatively slowly, we estimated aspects of the forest for each interval by grouping all panels sampled within a four year period. Monitoring is ongoing, but for the purposes of this manuscript we used data from one sub-plot for each plot sampled resulting in 432 sub-plots in Interval 1 (2002–2005), 860 sub-plots in Interval 2 (2006–2009), and 854 sub-plots in Intervals 3 (2010–2013) and 4 (2014–2017).

We analyzed data using seven tree species groups: All Pine (all *Pinus* sp. including *P. palustris*), Longleaf Pine, All Oak (all *Quercus* sp.), Live Oak (*Quercus virginiana*, *Quercus geminata*), Mesic Oak (*Quercus laurifolia*, *Quercus nigra*, *Quercus phellos*), Xeric Oak (*Quercus geminata*, *Quercus margaretta*, *Quercus laevis*, *Quercus incana*) and Other (species not included in Pine or All Oak, e.g. *Carya* sp., *Ulmus* sp., *Fraxinus* sp., *Nyssa* sp., *Taxodium sp.*), but have only reported results for Pine, Longleaf Pine, All Oak, and Other. We calculated estimates for Ichauway as a whole and for each of the 8 community types. All estimates were calculated in Program R (R Core Team, 2017) and the spsurvey package (Kincaid & Olsen, 2018) was used to determine average estimates per hectare and standard errors with adjustment for the number of sites sampled in each community type.

We calculated volume (m^3/ha) using DBH and tree height for all sampled living tree trunks over 10 cm DBH. Because we did not collect height data for all trees within a sub-plot, we modeled tree heights using equations and species-specific coefficients from Sheffield and Schweitzer (2002) and adjusted to account for site and community parameters influencing height development. We had 93 species-community groups with individual adjustment ratios. We created species-community groups based on similarities in ratios of known height to DBH and balanced by the number of individual trees with known height data (i.e., species or communities with few height measurements were grouped). Composition of species-community groups included single species in one or more communities or multiple species with similar growth patterns in multiple communities. Modeled tree heights were used to calculate volume. We calculated volume using southern region equations and species-specific coefficients from the USFS (Woodall, Heath, Domke, & Nichols, 2011). Using published equations and coefficients for calculations of height and volume allows for easier replication of our methods and comparison of our estimates of volume and change in volume to other small studies within the region or regional data. Published equations are also appropriate because our objectives are to examine changes with management and stand development rather than to accurately predict volumes as in a timber inventory. Additionally, we calculated average trees per hectare in 5 cm DBH classes across the property and for each community type by species group.

Changes in forest structure included ingrowth (trees growing into minimum measured diameter class), mortality, and net change in growing stock (living volume). Average ingrowth was calculated using new trees entering the 10–18 cm DBH size-class. We calculated percent mortality of all trees dying between the previous and next sampling interval for all mortality causes including harvest and calculated percent mortality by mortality cause. To calculate estimates and errors of net change in growing stock, we used the change analysis function from the spsurvey package in Program R. We calculated change in volume between each sampling interval and between Intervals 1 and 4. Changes were considered significant if the 95% CI did not overlap 0 ($\alpha = 0.05$). Annual rate of change was calculated by dividing the overall change from Interval 1 to 4 by the number of years between samples, 12. This is an average rate of change and actual annual changes likely differed throughout the study period.

Finally, to better understand how our management practices

influenced forest structure and dynamics, we examined two specific treatments: hardwood removal and planting of pine seedlings, and compared these to routine management. These were not experimental treatments, and both practices occurred across Ichauway with different areas receiving treatments at different times. Additionally, management treatments were not always applied to entire sub-plots. Since management occurred throughout the study period, the management status of a sub-plot could change over time, but remained assigned to a management category for all sampling intervals after management occurred. In each sample interval, sub-plots were assigned one management status: planted pine, hardwood removal, or routine management (e.g., prescribed fire, timber harvest). Sub-plot center points within 18 m of areas planted with pine were designated as pine plantation plots. Of the remaining sub-plots, those with center points within 18 m of areas where hardwood removal occurred after January 2000 were designated as hardwood removal plots. All remaining plots were considered routine management. We calculated metrics for each management treatment that would best reflect changes in managed areas over time. We used methods as described above to calculate volume, change in volume between each sample period and the first and last samples, ingrowth, and mortality for the three management categories.

We did not remove all hardwoods in hardwood removal areas, therefore we estimated volume of hardwood removed to better understand how this management practice affects forest dynamics and structure. Volume of hardwoods removed, both as actual volume and percent removed, from all areas undergoing hardwood removal (including those later planted in pine) was calculated using change in volume from the interval prior to hardwood removal to the first interval after hardwood removal occurred. Both volume and % original volume were calculated for each hardwood species group and by diameter class (10–18 cm, 18–26 cm, 26–34 cm, > 34 cm). While data were collected for understory and coarse woody debris, these results are not reported here due to space limitations.

3. Results

3.1. Volume and tree diameter distribution

Pines constituted the majority of the tree volume at Ichauway throughout the study period. Most of the pine volume was longleaf pine (Fig. 3) with ~80% of longleaf pine volume from trees in the > 34 cm DBH class. When examining volumes for individual community types this general pattern held for flatwoods, fluvial terrace, sand ridge, and upland community types; the dry terrace and tolerant depression communities had an even mix of pine and hardwood species, while the floodplain and intolerant depression communities were hardwood dominated.

Volume of pine trees increased throughout the study period between each interval for Ichauway (Table 3). This volume increase between each period was significant. Overall, pine tree volume between Intervals 1 and 4 increased 13.29 (± 2.03) m^3/ha or 1.11 m^3/ha/year on average. Pine volumes for each community increased over the entire study period except floodplains, which had no change (Table 3).

Volume of oak trees decreased between the first and second sampling period (Table 4), which was the period of most intense hardwood removal (Table 5). Between the second and third sample, oak tree volume decreased but to a lesser extent than the previous interval with intensive hardwood removal treatments. Oak tree volume increased between the third and fourth sample periods (Table 4). On average, oak tree volume decreased during the study period by -0.29 m^3/ha/year or -3.54 (± 1.54) m^3/ha. The intolerant depression and sand ridge communities had the greatest reduction in oak volume during the time of intense hardwood removal (Interval 1; Table 4).

The general diameter distribution of longleaf pine trees remained consistent over the study period with the highest number of trees in the smallest size class (10–15 cm DBH) and a small peak in trees with a DBH of 35–50 cm (Fig. 4). There was an increase in the number of longleaf pine trees with DBH of 10–25 cm and 55 + cm per hectare over the study period (Fig. 4). Average number of oak trees per hectare decreased over time with the largest decreases in the smallest diameter class (10–15 cm DBH; Fig. 5). Oak tree density remained fairly stable between Intervals 3 and 4 with a slight, non-significant increase in the smallest diameter class and largest diameter class (60 + cm DBH; Fig. 5).

3.2. Stand dynamics

Average volume of new pine trees (ingrowth) increased throughout the study period across Ichauway (Fig. 6). Approximately 70–90% of pine ingrowth was from longleaf pine. Oak ingrowth varied throughout the study for Ichauway as a whole (Fig. 7). Oak ingrowth in each community was variable or stable, except for the fluvial terrace which had a slight positive trend, 0.06 (± 0.05) – 0.25 (± 0.08) m^3/ha.

Throughout the study period (Intervals 2 through 4) and across

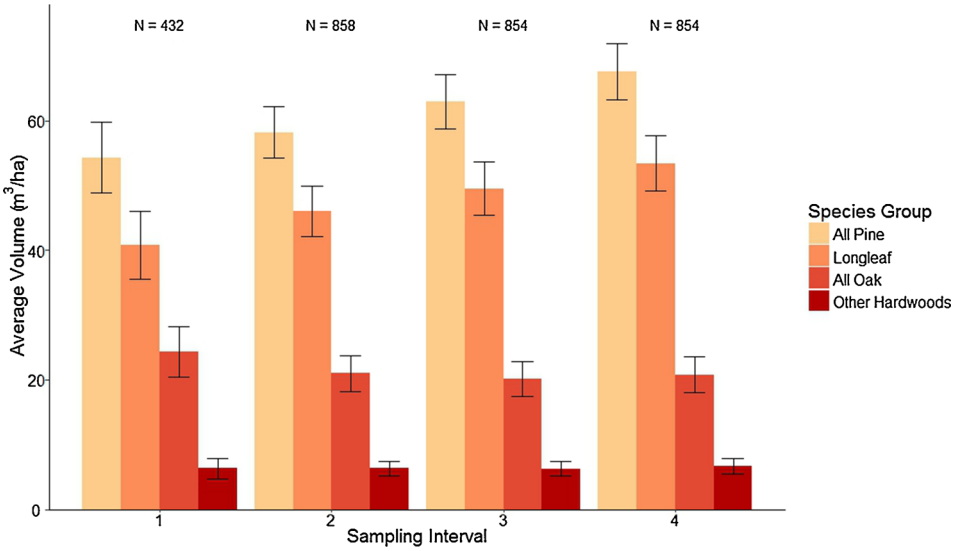

Fig. 3. Average volume (m^3/ha) of all living trees across Ichauway near Newton, GA, USA from 2002 – 2017. Sampling intervals include samples collected over 4 year period (1: 2002–2005; 2: 2006–2009; 3: 2010–2013; 4: 2014–2017).

Table 3
Overall change in volume (m^3/hectare) of pine trees (*Pinus* sp.) between each sampling interval (1: 2002–2005; 2: 2006–2009; 3: 2010–2013; 4: 2014–2017) and for the entire study period by community type on Ichauway near Newton, GA, USA with 95% confidence intervals in parentheses. Asterisks indicate significant change in volume between intervals at $\alpha = 0.05$.

Community	1 to 2	2 to 3	3 to 4	1 to 4
Ichauway	3.9 (0.1 – 7.7)*	4.7 (3.8 – 5.6)*	4.7 (3.9 – 5.5)*	13.3 (9.3 – 17.3)*
Dry Terrace	-0.7 (-8.3 – 6.8)	5.3 (3.5 – 7.2)*	6.6 (5.1 – 8.1)*	11.2 (2.8 – 19.6)*
Flatwoods	-0.7 (-9.4 – 8.0)	4.9 (3.8 – 6.1)*	6.9 (5.8 – 8.1)*	11.2 (2.2 – 20.2)*
Floodplain	1.7 (-6.4 – 9.7)	-0.8 (-3.5 – 1.9)	1.4 (-0.2 – 2.9)	2.3 (-6.9 – 11.4)
Fluvial Terrace	11.5 (0.4 – 22.6)*	6.0 (4.6 – 7.4)*	4.5 (2.5 – 6.5)*	22.0 (10.2 – 33.8)*
Intolerant Depression	2.7 (-5.7 – 11.1)	2.2 (0.2 – 4.1)*	5.9 (4.0 – 7.8)*	10.8 (1.8 – 19.8)*
Sand Ridge	11.4 (3.2 – 19.5)*	3.8 (2.3 – 5.3)*	6.1 (4.6 – 7.6)*	21.3 (12.4 – 30.1)*
Tolerant Depression	1.8 (-3.3 – 7.0)	2.3 (1.5 – 3.2)*	2.4 (1.5 – 3.3)*	6.5 (0.4 – 12.7)*
Upland	3.6 (-2.3 – 9.5)	5.2 (4.0 – 6.5)*	4.2 (2.6 – 5.8)*	13.0 (6.9 – 19.1)*

Table 4
Overall change in volume (m^3/hectare) of oak trees (*Quercus* sp.) between each sampling interval (1: 2002–2005; 2: 2006–2009; 3: 2010–2013; 4: 2014–2017) and for the entire study period by community type on Ichauway near Newton, GA, USA with 95% confidence intervals in parentheses. Asterisks indicate significant change in volume between intervals at $\alpha = 0.05$.

Community	1 to 2	2 to 3	3 to 4	1 to 4
Ichauway	-3.4 (-6.3 – -0.4)*	-0.8 (-1.6 – 0.0)*	0.6 (0.1 – 1.2)*	-3.5 (-6.6 – -0.5)*
Dry Terrace	-0.2 (-9.5 – 9.0)	1.6 (0.8 – 2.5)*	1.0 (-1.1 – 3.0)	2.4 (-6.3 – 11.0)
Flatwoods	-1.7 (-7.7 – 4.3)	-0.9 (-3.6 – 1.8)	1.7 (0.7 – 2.6)*	-0.9 (-7.4 – 5.6)
Floodplain	-3.6 (-14.8 – 7.5)	3.5 (0.9 – 6.1)*	2.3 (-0.5 – 5.0)	2.1 (-9.6 – 13.9)
Fluvial Terrace	-0.6 (-8.9 – 7.7)	-0.9 (-3.1 – 1.3)	-2.2 (-5.9 – 1.4)	-3.7 (-11.8 – 4.4)
Intolerant Depression	-22.6 (-33.1 – -12.1)*	1.4 (0.1 – 2.7)*	3.0 (2.0 – 4.1)*	-18.2 (-28.5 – -7.9)*
Sand Ridge	-8.9 (-14.9 – -3.0)*	0.8 (0.1 – 1.4)*	2.2 (1.3 – 3.0)*	-6.0 (-11.8 – -0.1)*
Tolerant Depression	-2.2 (-7.3 – 2.9)	-1.5 (-3.4 – 0.3)	-0.6 (-1.6 – 0.3)	-4.3 (-9.8 – 1.1)
Upland	-1.7 (-5.7 – 2.2)	-1.8 (-3.3 – -0.3)*	0.1 (-0.5 – 0.8)	-3.4 (-7.5 – 0.7)

Table 5
Hectares of hardwood (primarily *Quercus* sp.) removal from 2000 to 2017 on Ichauway near Newton, GA, USA by community type and removal year.

Community	2000-2005	2006-2009	2010-2013	2014-2017	Total
Ichauway Total	2255.2	1318.8	225.7	69.2	3868.9
Dry Terrace	46.4	94.4	56.3	14.4	211.5
Flatwoods	86.8	125.5	37.7	0.7	250.7
Floodplain	3.4	13.6	0.1	0.8	17.9
Fluvial Terrace	32.9	73.0	30.6	3.4	139.9
Intolerant Depression	156.0	69.2	18.1	3.2	246.5
Sand Ridge	258.8	73.0	16.5	3.9	352.2
Tolerant Depression	18.4	27.9	7.0	0.0	53.3
Upland	1652.5	842.1	59.4	42.9	2596.9

Ichauway, percent mortality of pine was relatively stable, 3.66% (± 0.78), 2.98% (± 0.39), and 4.56% (± 0.58), with a slight increase in mortality during Interval 4. Pine mortality was primarily attributed to timber harvest, 1.04 (± 0.29) – 2.44% (± 0.750), and unknown causes, 0.64 (± 0.17) – 1.49% (± 0.25). Lightning, fire, suppression, and environment (e.g., erosion, flooding) caused minor mortality during each sample interval, with total mortality due to these causes over the study period < 1%. Oak mortality decreased during each interval: 12.28% (± 1.44), 7.39% (± 0.80), and 4.85% (± 0.59). This reduction in mortality was due to decreased hardwood removal activities and therefore reduced harvest mortality. Other than harvest, oak mortality was also primarily attributed to unknown factors which remained a consistent cause throughout the study period across Ichauway, 3.20 (± 0.72) – 3.52% (± 0.52). Fire, 0.15 (± 0.09) – 0.19% (± 0.10), and environment, 0.02 (± 0.02) – 0.08% (± 0.03), were two causes of mortality throughout the study period but affected a small number of oak trees.

3.3. Management specific results

Areas receiving routine management were found throughout Ichauway in all communities. Volume of all pines increased throughout the study period in routine management areas from 59.52 (± 3.22) – 74.11 (± 3.00) m^3/ha. Longleaf pine also increased and made up the majority of the all pine volume, 48.61 (± 3.21) – 63.25 (± 3.04) m^3/ha in these areas. Some of the increase in pine tree volume was due to ingrowth, 0.11 (± 0.02), 0.30 (± 0.04), and 0.59 (± 0.08) m^3/ha for Intervals 2–4, respectively (Fig. 6). Over the study period, oak tree volume remained fairly stable with a slight decrease in routine management areas, 27.34 (± 2.16), 25.98 (± 1.76), 23.95 (± 1.76), and 24.07 (± 1.70) m^3/ha. Accordingly, change in oak volume over the study period was not statistically relevant, -3.27 (± 2.14) m^3/ha. Other hardwood tree volume remained relatively stable with a slight increase, 8.38 (± 1.02) – 10.74 (± 0.97) m^3/ha. The increase in other hardwood volume in routine management areas over the study period was different than 0, 2.36 (± 0.72) m^3/ha. Routine management forests had higher oak ingrowth than the forest population on Ichauway as a whole (including planted pine and hardwood removal areas; Fig. 7), but this difference was not statistically significant. There were no differences in mortality over time for pine or oak in routine management areas, but oak mortality was slightly higher than pine mortality (Table 6).

Pines were primarily planted in the upland community and also in the dry terrace, flatwoods, fluvial terrace, intolerant depression, and sand ridge communities (Table 7). Total pine volume in planted pine areas increased over the study period from 29.93 (± 7.51) – 50.03 (± 3.59) m^3/ha across Ichauway. Increases in volume throughout the study period for longleaf pine, 22.17 (± 2.74) m^3/ha, were slightly greater than the total increase in all pine volume, 20.10 (± 6.33) m^3/ha, most likely due to increased timber harvest of other pine species in pine plantations. Planted pine areas had the highest pine ingrowth rates compared to all other management classes (Fig. 6). Oak volume in planted pine areas decreased slightly after the first interval and then

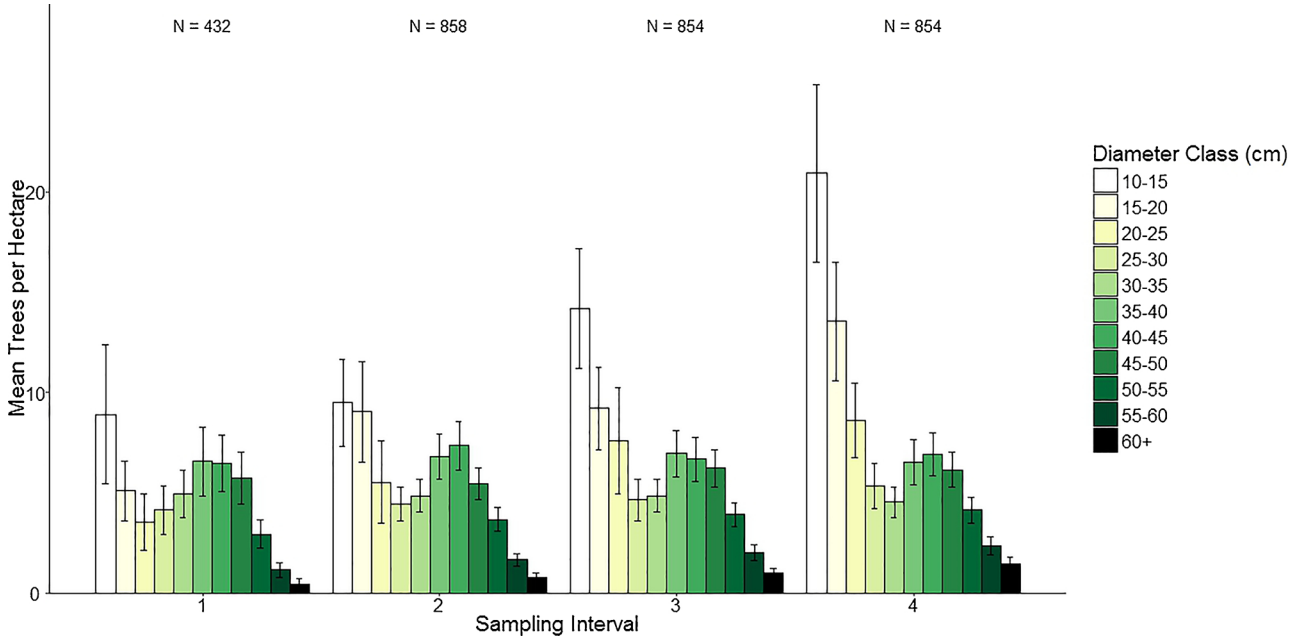

Fig. 4. Average number of longleaf pine trees per hectare by diameter class across Ichauway near Newton, GA, USA from 2002 – 2017. Sampling intervals include samples collected over 4 year period (1: 2002–2005; 2: 2006–2009; 3: 2010–2013; 4: 2014–2017).

remained relatively stable, 16.63 (± 7.82), 10.75 (± 3.98), 9.33 (± 3.83), and 10.39 (± 4.08) m^3/ha, while other hardwoods increased after the first interval and then remained consistent at low levels, 0.26 (± 0.16), 0.57 (± 0.24), 0.44 (± 0.19), and 0.48 (± 0.19) m^3/ha. Changes in volume over time were not significant in planted pine areas. Pine mortality in planted pine sub-plots was similar to routine management in Intervals 2 and 3 but increased during Interval 4 due to timber harvest (Table 6). Hardwood removal prior to planting pines caused increased oak mortality in Interval 2 (Table 6).

We also estimated volume of trees in areas that were not planted with pine but had hardwood removal treatment after January 2000. These areas were found in every community type but predominantly in upland areas. Non-planted hardwood removal areas were primarily in stands with mature pines; all pine volume, 46.60 (± 7.44) – 64.40 (± 4.34) m^3/ha, and longleaf pine volume, 32.21 (± 5.60) – 49.59 (± 3.92) m^3/ha, in these areas was higher than in areas with planted pines. As expected, pine ingrowth was much lower in these non-planted areas when compared to areas with planted pine (Fig. 6). Oak tree ingrowth was also lowest in non-planted hardwood removal areas when compared to all other management classes (Fig. 7). There were minor

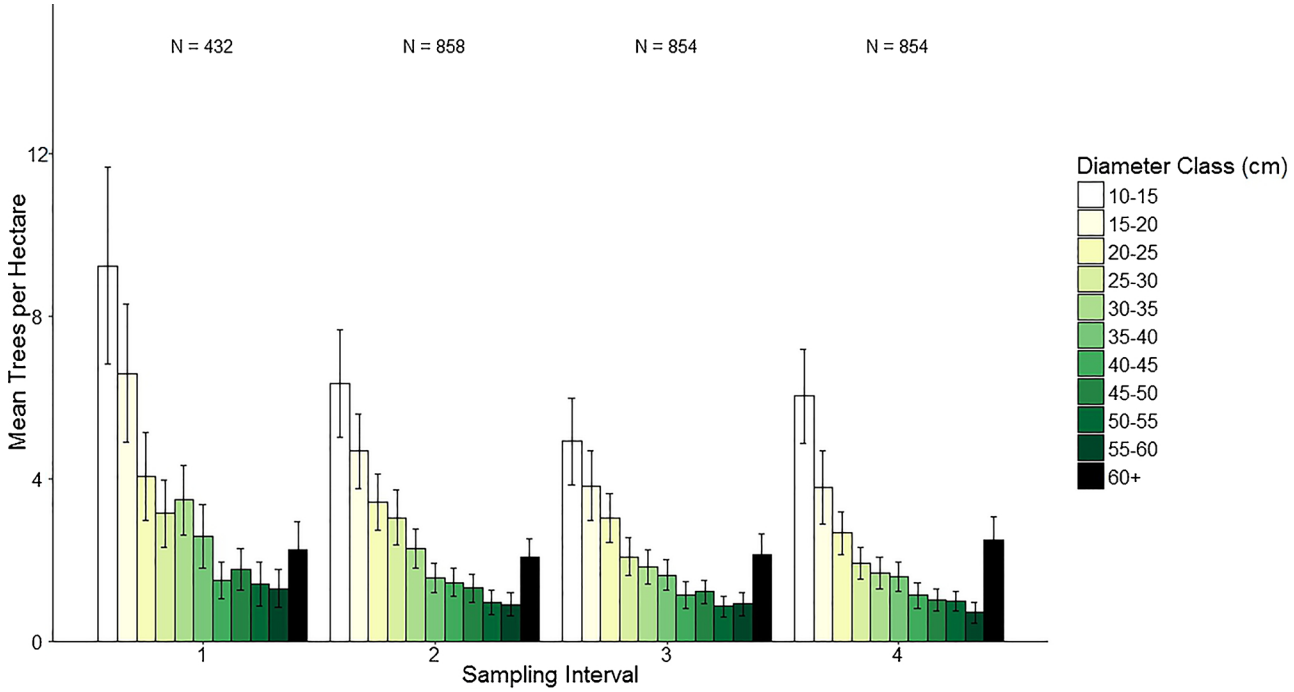

Fig. 5. Average number of oak trees per hectare by diameter class across Ichauway near Newton, GA, USA from 2002 – 2017. Sampling intervals include samples collected over 4 year period (1: 2002–2005; 2: 2006–2009; 3: 2010–2013; 4: 2014–2017).

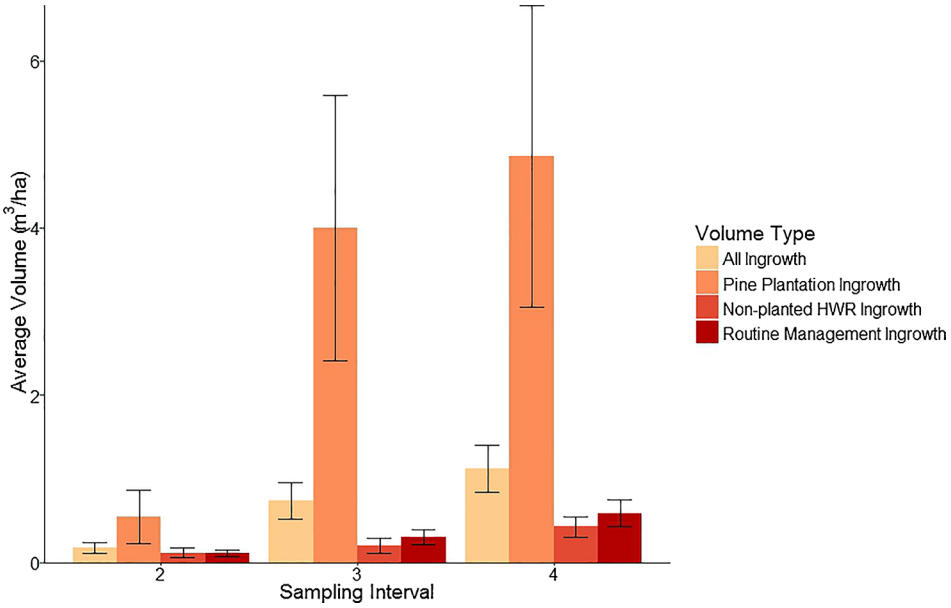

Fig. 6. Average volume (m^3/ha) of all new pine trees (ingrowth into 10-cm DBH class) across Ichauway near Newton, GA, USA from 2006 to 2017 with specific estimates for each management category, pine plantations, hardwood removal (HWR), and routine management. Sampling intervals include samples collected over 4 year period (2: 2006–2009; 3: 2010–2013; 4: 2014–2017).

increases in total oak volume, 11.75 (± 3.88), 13.19 (± 2.42), 16.85 (± 2.39), and 18.33 (± 2.53) m^3/ha, and other hardwood volume, 0.02 (± 0.01), 0.72 (± 0.30), 1.05 (± 0.33), and 1.00 (± 0.31) m^3/ha, over the study period. As expected, oak mortality was highest in hardwood removal areas during Intervals 2 and 3 (mortality occurred before samples were collected in these intervals) due to the management activity. Oak mortality in Interval 4 was similar to routine management areas since hardwood removal activities were greatly reduced (Table 6). Pine mortality in hardwood removal areas in Interval 2 was higher than Intervals 3 and 4 due to areas overlapping with pine timber harvest (Table 6).

We removed 17.32 (± 3.30) m^3/ha of oak volume and 1.00 (± 0.21) m^3/ha of other hardwood volume on average from areas where hardwood removal management occurred (including areas where pines were later planted; Table 5). This represented 40.01% (± 4.17) of oak and 15.58% (± 3.10) of other hardwood volume within removal areas. The percentage of trees cut in each diameter class varied over the sample intervals. In areas harvested between Intervals 1 and 2, the majority of the volume removed were oak trees > 34 cm DBH, 51.02% (± 8.96), and 10–18 cm DBH, 20.84% (± 7.71). Volume of oak trees removed from each diameter class between Intervals 2 and 3 was relatively even, 20.02% (± 4.67) – 28.05% (± 6.81). Fewer areas had trees harvested between Intervals 3 and 4 (Table 5), and in this time frame the majority of oak trees removed were 26–34 cm DBH, 46.99% (± 21.69) and > 34 cm DBH, 25.23% (± 15.37).

4. Discussion

The restoration of the longleaf pine ecosystem is an extended process occurring over decades due to the natural history of longleaf pine associated species, complexity of ecosystem functions, and a wide range of desired endpoints (Jack & McIntyre, 2018). However, our analysis of forest volume change using long-term monitoring data after 16 years indicates that we are successfully achieving our overall restoration goals of enhancing the fire-maintained longleaf pine ecosystem and associated communities on site through our management actions.

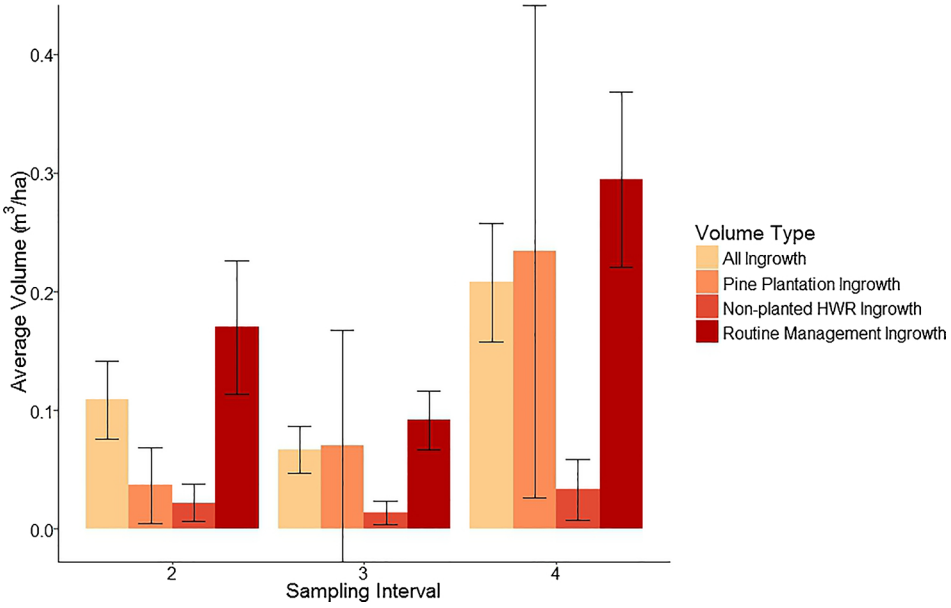

Fig. 7. Average volume (m^3/ha) of all new oak trees (ingrowth into 10–18 cm DBH class) across Ichauway near Newton, GA, USA from 2006 to 2017 with specific estimates for each management category, pine plantations, hardwood removal (HWR), and routine management. Sampling intervals include samples collected over 4 year period (2: 2006–2009; 3: 2010–2013; 4: 2014–2017).

Table 6
Percent morality with 95% CI in parentheses for pine (*Pinus* sp.) and oak (*Quercus* sp.) trees by management category for each sampling interval (2: 2006–2009; 3: 2010–2013; 4: 2014–2017) on Ichauway near Newton, GA, USA.

Species	Management	2	3	4
Pine	Routine Management	2.7% (1.0 – 4.5)	2.8% (1.8 – 3.8)	3.8% (2.3 – 5.3)
	Pine Plantation	3.4% (0.2 – 6.7)	3.3% (1.3 – 5.2)	10.3% (6.4 – 14.1)
	Hardwood Removal	5.1% (1.6 – 8.6)	3.2% (1.9 – 4.6)	3.2% (1.4 – 5.1)
Oak	Routine Management	6.2% (3.6 – 8.9)	4.9% (3.4 – 6.4)	5.4% (3.8 – 7.1)
	Pine Plantation	13.7% (3.5 – 23.8)	1.2% (0.1 – 2.3)	0.4% (-0.1 – 0.8)
	Hardwood Removal	23.1% (16.5 – 29.6)	15.1% (10.9 – 19.2)	5.7% (3.4 – 7.9)

Table 7
Hectares of planted pines (*Pinus* sp.) on Ichauway near Newton, GA, USA by community type and planting year.

Community	1900-1950	1951-1990	1991-2000	2001-2013	Total
Ichauway Total	117.1	132.9	285.3	643.4	1178.7
Dry Terrace	35.6	19.0	5.1	58.6	118.3
Flatwoods	0.0	2.2	0.9	10.9	14.0
Floodplain	0.0	0.0	0.6	1.2	1.8
Fluvial Terrace	0.0	0.0	2.4	3.9	6.3
Intolerant Depression	0.1	0.1	3.0	43.4	46.6
Sand Ridge	0.0	55.3	11.7	48.3	115.3
Tolerant Depression	0.0	0.1	0.0	0.1	0.2
Upland	81.5	56.3	261.6	477.0	876.4

Management actions and forest growth have led to an increase in pine volume, particularly for longleaf pine, across Ichauway. The majority of this increase occurred in site-appropriate communities (areas where longleaf pine typically and historically occurred). Change in volume included losses due to mortality, thus we detected a net gain in volume due to pine growth. Increases in the smallest size classes were indicated by ingrowth and average number of trees per hectare in the 10–15 cm diameter class.

The forest structure on Ichauway as described in our analysis indicates that our forest is further along the restoration continuum than most longleaf pine restoration sites within the region, many of which were afforested. Approximately 80% of longleaf pine volume on Ichauway is from trees over 34 cm DBH, almost 30% more than the volume in this size class across the eastern Coastal Plain region (Oswalt et al., 2012). Across the range, there is proportionally twice as much longleaf pine volume in the 10–15 cm diameter class than at Ichauway (Oswalt et al., 2012). Differences in large and small trees on Ichauway versus the longleaf pine range as a whole is more pronounced when looking at the diameter distribution. Across the region, each size class over 50 cm DBH has approximately 1% as many pine trees as the 10–15 cm diameter class (Oswalt et al., 2012), whereas on Ichauway each of these size classes has 7–20% of the number of trees in the 10–15 cm DBH size class (Sample Interval 4). Using diameter distributions as an indicator of the proportion of ingrowth to larger trees, later samples from Ichauway (Sample Intervals 3 and 4) are more similar to old growth longleaf pine forests in the coastal plain of Georgia and mountain region (montane longleaf pine) of Alabama with approximately twice as many trees in the 10–15 cm DBH diameter class than in 40–45 cm DBH (Noel, Platt, & Moser, 1998; Platt, Evans, & Rathbun, 1988; Varner, Kush, & Meldahl, 2003. The tree distribution at Ichauway differs from old growth forests due to a slightly more pronounced dip in number of trees with a 20–40 cm DBH, a characteristic also found in the diameter distribution for a secondary forest in Mississippi (Noel et al., 1998). These dips are likely due to periods of reduced regeneration and recruitment during stand development of these second growth forests.

Natural mortality of pine was a relatively unimportant aspect of forest dynamics at Ichauway during the sampling period ranging from 1.22 to 2.68% over a four year period. Annual mortality rates for the region are just over 1% (Oswalt et al., 2012) with studies in old-growth longleaf pine reporting annual mortality of 0–1% (Platt & Rathbun, 1993). Similar to previous reports of pine mortality on the study area and across the region, lightening and suppression were two of the most identifiable natural causes of mortality (Oswalt et al., 2012; Palik & Pederson, 1996; Platt & Rathbun, 1993). Most of the total mortality at Ichauway was through harvests for hardwood removal or of pine timber, but these harvests affected a small portion of the total population. In some communities, management activities such as hardwood removal caused substantial decreases in oak volume. These decreases exceeded overall oak growth across the property resulting in negative changes in oak volume during intense hardwood removal phases. However, increases in oak volume by Interval 4 indicated that oak volume recovered over time as remaining trees grew and new individuals entered the measured population, as suggested by both ingrowth and average tree density for the smallest diameter class.

Comparison of forest management practices provides early insight into the effectiveness of our restoration process. As expected, the greatest increase in pine ingrowth over the study period occurred in planted pine areas. Ingrowth of pine increased during the survey period for all management types indicating that we are increasing recruitment into the population even without planting pines. Routine management and non-planted hardwood removal areas had comparable values for pine ingrowth during all sample intervals. We found no difference in pine volume metrics or dynamics between areas with routine management and non-planted hardwood removal management, but these values may diverge as the LFM project continues. Hardwood removal had a negative impact on ingrowth of oak trees in comparison to routine management despite removing less than half of the oak volume and less than a quarter of the other hardwood volume available in all hardwood removal areas. Differences in mortality across years and management categories was primarily related to the timing of management activities. High oak mortality recorded during Sample Intervals 2 and 3 in hardwood removal plots relates to increased hardwood removal activities early in the study period. Increased timber harvest prior to and during Sample Interval 4 is reflected as higher pine mortality in pine plantation plots in the latest sampling interval.

Beyond providing indicators for the impacts of management on forest composition and structure, data from LFM plots provide information for scientific inquiry. Brantley, Stuber, Rutledge, and Jack, (2017) used data from LFM plots to demonstrate a reduction in evapotranspiration related to the removal of mesic oaks. This suggests the removal of mesic oaks, as a part of restoration, may enhance water conservation properties of the longleaf pine ecosystem (Brantley, Vose, Band, & Wear, 2018). Additionally, the LFM data were used in conjunction with wildlife monitoring data to develop biometric habitat models and meet several objectives in evaluating desired ecological conditions for wildlife species representative of the longleaf pine ecosystem. The results of that project were used to help define desired conditions for open pine woodland and savanna within the Gulf Coastal Plain and Ozarks Landscape Conservation Cooperative (L. M. Conner, Smith, & Schlimm, 2016).

Information gathered through the long term forest monitoring process will be used to refine longleaf pine restoration on Ichauway and increase understanding of effects on the longleaf pine system from

management activities. Additional lines of inquiry include long-term forest changes associated with restoration and the impacts of management and restoration on wildlife communities. Some relevant questions include: effects of hardwood removal on pine growth and regeneration; appropriate fire regime to maintain a reduced hardwood over-story and interactions with coarse-woody debris deposition (Hiers, O'Brien, Will, & Mitchell, 2007; Loudermilk, Hiers, & O'Brien, 2018); utility of multiple applications of hardwood removal for restoration; forest characteristics that impact the establishment of natural longleaf regeneration (Jack & Pecot, 2018); and response of longleaf associated wildlife species or communities to restoration (e.g., R. N. Conner, Shackelford, Schaefer, Saenz, & Rudolph, 2002; Kirby, Muller, Chamberlain, & Conner, 2017; Perkins, Conner, & Howze, 2008).

The restoration efforts for the longleaf pine system on Ichauway have implications for the wildlife community. We have successfully increased longleaf pine forests and therefore increased suitable habitat for longleaf endemic species such as the pine snake (*Pituophis melanoleucus*), red-cockaded woodpecker (*Leuconotopicus borealis*), Bachman's sparrow (*Peucaea aestivalis*), gopher tortoise (*Gopherus polyphemus*), and fox squirrel (*Sciurus niger niger*; L. M. Conner et al., 2016). Specifically, increases in the number of longleaf pine trees in larger diameter classes will allow for increased natural cavity construction and potentially better foraging habitat for red-cockaded woodpeckers (R. N. Conner, Rudolph, Saenz, & Schaefer, 1994; Engstrom & Sanders, 1997; Zwicker & Walters, 1999). This increase in nesting and foraging habitat should result in increased populations, productivity, and group size (US Fish & Wildlife Service, 2003). The reduction in hardwoods across the property may affect wildlife species more dependent on these habitat types. For example, eastern rat snakes have larger home ranges on Ichauway in comparison to other areas with more hardwood habitat (Howze, Sash, Carroll, & Smith, 2019).

Effects of management, such as appropriate fire regime, will be used to inform an adaptive management program and allow us to be more efficient practitioners of longleaf restoration. Based on our current results, future management can be adapted by revisiting hardwood removal areas to assess increases in oak volume and ingrowth and determining necessity and type of retreatment. Additionally, we can increase natural pine regeneration (and thereby increase the ratio of natural to planted regeneration) through overstory thinning and small gap creation. Differentiating between effects of management activities and changes due to other (i.e., climate change) causes will be difficult, and if static restoration-goals are used they may never be achieved (Golladay et al., 2016). Alternatively, variable objectives can be established with the use of dynamic reference models which will create a baseline for changes due to natural variation (Hiers et al., 2012; Kirkman et al., 2013). At this point in our study, variation in temperature across intervals is minimal, but there was a difference of 1000 mm in total rainfall between Sampling Interval 1 and 3 due to above average rainfall 3 of 4 years in Interval 1 and below average rainfall 3 of 4 years in Interval 3. Increased variation in rainfall may affect longleaf pine systems by increasing tree stress and fire intensity during long periods of drought. However, the longleaf pine ecosystem may be more resilient to predicted changes in climate (e.g. variation in precipitation, increased temperature, higher intensity and frequency of hurricanes) due to the biology of longleaf pine and the ecosystem (Addington et al., 2006; Johnsen, Butnor, Kush, Schmidtling, & Nelson, 2009; Mitchell et al., 2014; Samuelson, Stokes, & Johnsen, 2012).

Question-driven monitoring programs can aid in understanding ecological processes but may fail to extrapolate well to larger scales (Lindenmayer & Likens, 2010b). Building on our detailed site-based analysis, we will address broader restoration questions related to the temporal scale of management response and long-term effects of restoration and management activities. This will lead to the development of conceptual and predictive models to aid broader restoration of longleaf pine across its former range. Additionally, we believe a comparison of our LFM results with those of monitoring programs conducted on a regional or national scale (e.g. FIA, National Ecological Observatory Network) will provide opportunities to investigate and better understand the processes behind forest change due to active forest restoration and natural processes such as climate change at a broader scale. As we move forward, our data collection and detailed analyses will remain based on Ichauway but we will consider how our findings relate to longleaf pine systems across the southeast region as suggested by Lindenmayer and Likens (2010a).

It is important to re-evaluate objectives and methods in an adaptive monitoring framework as we continue our long-term monitoring program. Modifications and refinements to the program will be necessary as questions evolve. Currently we are limited by the temporal aspect of our study design. For example, how do our management activities, such as fire and hardwood removal, interact with rainfall to affect herbaceous and woody stem ground cover? Answering this question requires more precise temporal data with some sub-plots having micro-plot data collected in the year following the full sub-plot data collection. This additional sampling would add partial augmentation to our current serially alternating study design (Urquhart, 2012). There are also questions that we are unable to address due to lack of data, including, direct and indirect effects of management activities on insect population dynamics and the resulting effects on bird communities. Our current sample size, which represents < 1% of Ichauway, was adequate to estimate averages across the property and within each community type (based on low SE for most estimates), but we need to determine if the current number of sample sites is appropriate for the more detailed analyses we plan to conduct. Our long-term ecological monitoring program combines data from multiple disciplines and we have shown that a small part of our data set can be used to evaluate restoration. Further, we believe that this study demonstrates success in the early steps of longleaf pine restoration and conservation on Ichauway and lays the groundwork for more detailed assessments of our restoration and management practices in the future.

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